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A COMPARATIVE STUDY OF NAVIER-STOKES CODES FOR HIGH-SPEED FLOWS

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A comparative study has been made with four different codes for solving the compressible Navier-Stokes equations using three different test problems. The first of these cases was hypersonic flow through the P8 inlet, which represents inlet configurations typical of a hypersonic airbreathing vehicle. The free-stream Mach number in this case was 7.4. This 2-D inlet was designed to provide an internal compression ratio of 8. Initial calculations were made using two state-of-the-art finite-volume upwind codes, CFL3D and USA-PG2, as well as NASCRIN, a code which uses the unsplit finite-difference technique of MacCormack. All of these codes used the same algebraic eddy-viscosity turbulence model. In the experiment, the cowl lip was slightly blunted; however, for the computations, a sharp cowl leading edge was used to simplify the construction of the grid. Although the overall features of the inlet flow field were predicted reasonably well, discrepancies between the computed and experimental profiles of pitot pressure and total temperature were found for all of the codes. Calculations were then made with the two finite-volume upwind codes using a patched-grid approach which allowed the use of a blunt cowl tip. This produced a more accurate location for the cowl leading-edge shock and thus an improvement in the location of the resultant shock reflections within the inlet.

The second test problem was the supersonic (Mach 3.0) flow in a three-dimensional corner formed by the intersection of two wedges with equal wedge angles of 9.48 degrees. The flow in such a corner is representative of the flow in the corners of a scramjet inlet. Calculations were made for both laminar and turbulent flow and compared with experimental data. The three-dimensional versions of the three codes used for the inlet study (CFL3D, USA-PG3, and SCRAMIN, respectively) were used for this case. For the laminar corner flow, a fourth code, LAURA, which also uses recently-developed upwind technology, was also utilized. It was found that the complex flow structure was qualitatively predicted by all of the codes. Furthermore, with a sufficiently-refined grid, all four codes gave identical results for the laminar case.

The final test case is the two-dimensional hypersonic flow over a compression ramp. In this case, the flow is laminar with a free-stream Mach number of 14.1. In the experiment, the ramp angle was varied to change the strength of the ramp shock and the extent of the viscous-inviscid interaction. Calculations have been made for the 24-degree ramp configuration which produces a large separated-flow region that extends upstream of the corner. All of the codes predicted the strong-interaction structure observed experimentally. However, a wide variation in the predicted extent of separation was found for the grid that was used.

DESCRIPTION OF CODES

- CFL3D
  - Written by James L. Thomas
  - Upwind-biased Roe scheme for pressure and convective terms
  - Central-difference treatment of viscous terms
  - Approximate-factorization time differencing

- USA-PG3
  - Written by Sukumar Chakravarthy
  - Roe scheme for convective and pressure terms
  - Central-difference treatment of viscous terms
  - Approximate-factorization time differencing

DESCRIPTION OF CODES

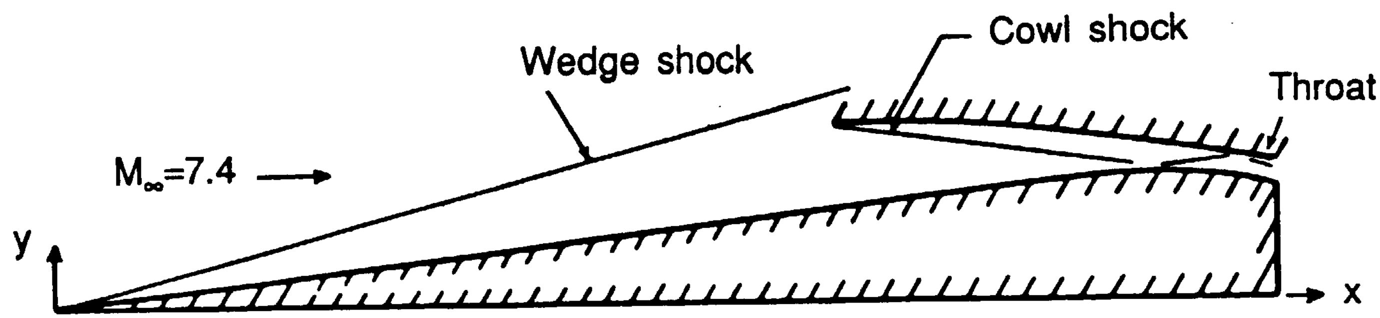
- LAURA
  - Written by Peter A. Gnoffo
  - Symmetric TVD scheme with Roe averaging
  - Alternating directional-sweep Gauss-Seidel relaxation
  - Laminar flow only at present time

- NASCRIN and SCRAMIN
  - Written by Ajay Kumar
  - Explicit unsplit MacCormack scheme

TEST PROBLEMS

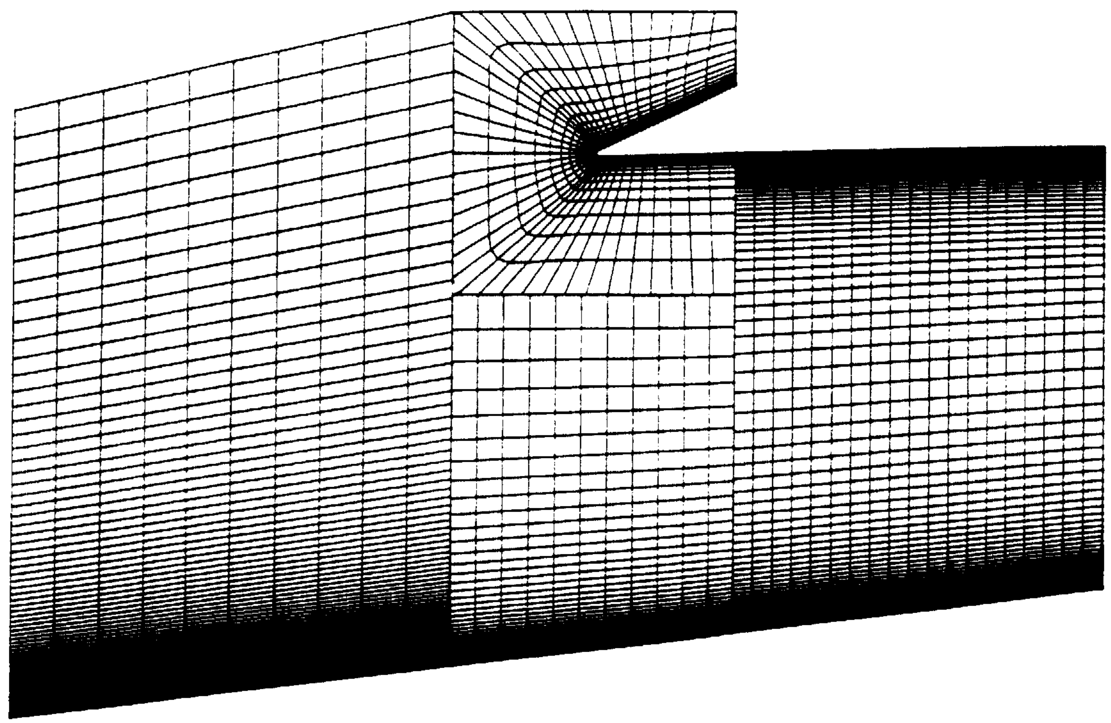
- P8 Inlet
  - 2-D, transitional
  - Experimental data: Gnos et al.
- Symmetric-wedge corner
  - 3-D, laminar and turbulent
  - Experimental data: West and Korkegi
- Hypersonic compression corner
  - 2-D, laminar
  - Experimental data: Holden and Moselle

P8 INLET



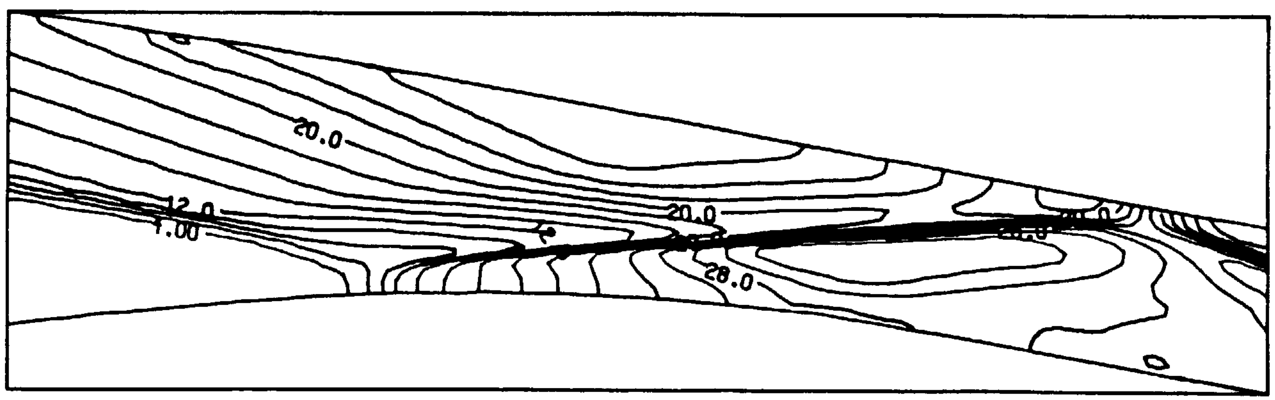
GRIDS NEAR INLET ENTRANCE

Patched-grid computations



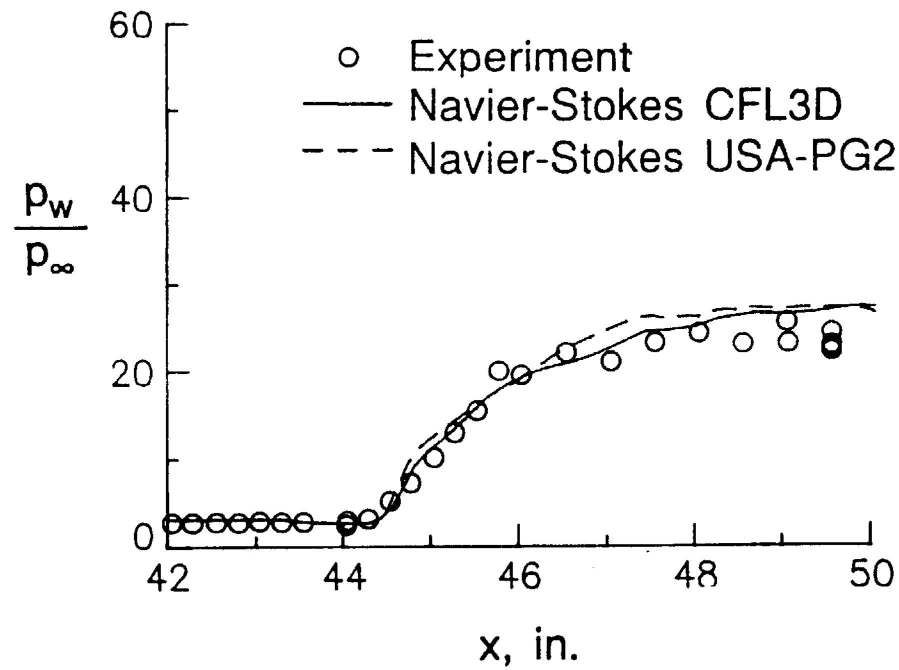
COMPUTED INLET PRESSURE

USA-PG2
Transitional computation
Sharp cowl leading edge



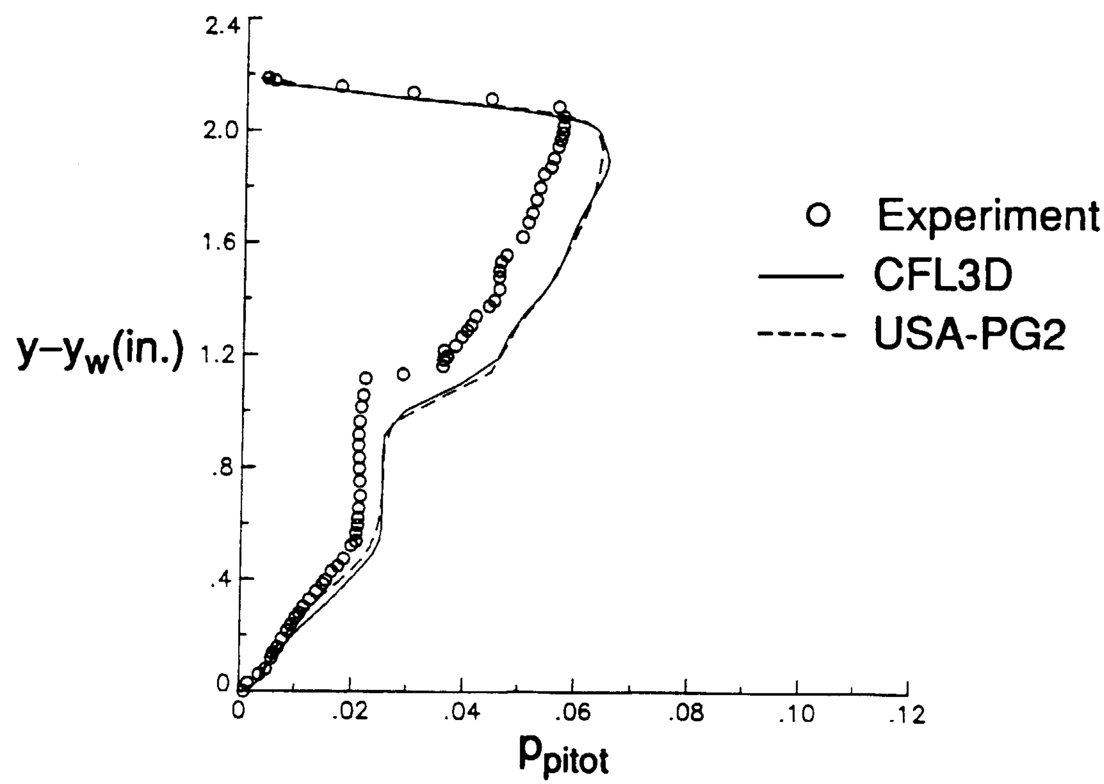
CENTERBODY PRESSURE

Blunt cowl leading edge



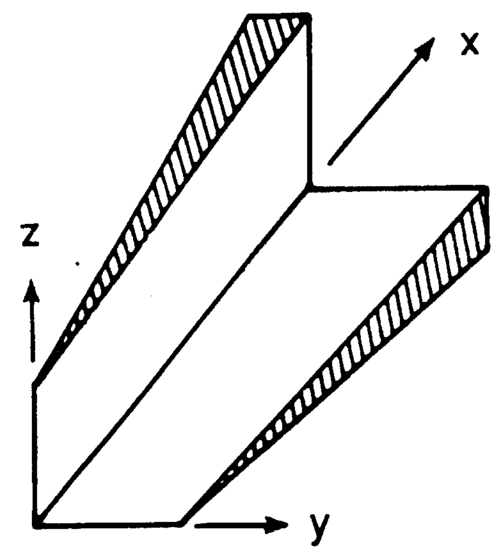
PITOT PRESSURE PROFILE

x = 40.9 in.
Blunt cowl leading edge

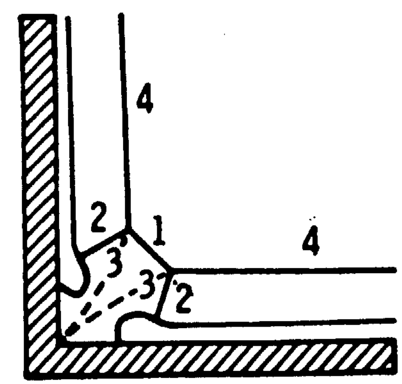


CORNER FLOW

$M_\infty = 3.0$

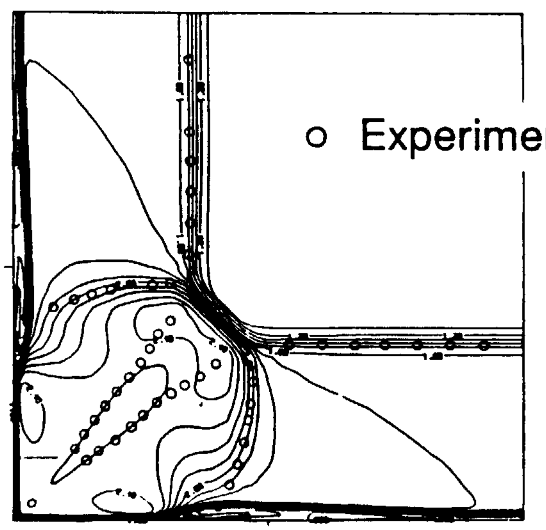


1 Corner shock
2 Internal shock
3 Slip line
4 Wall shock

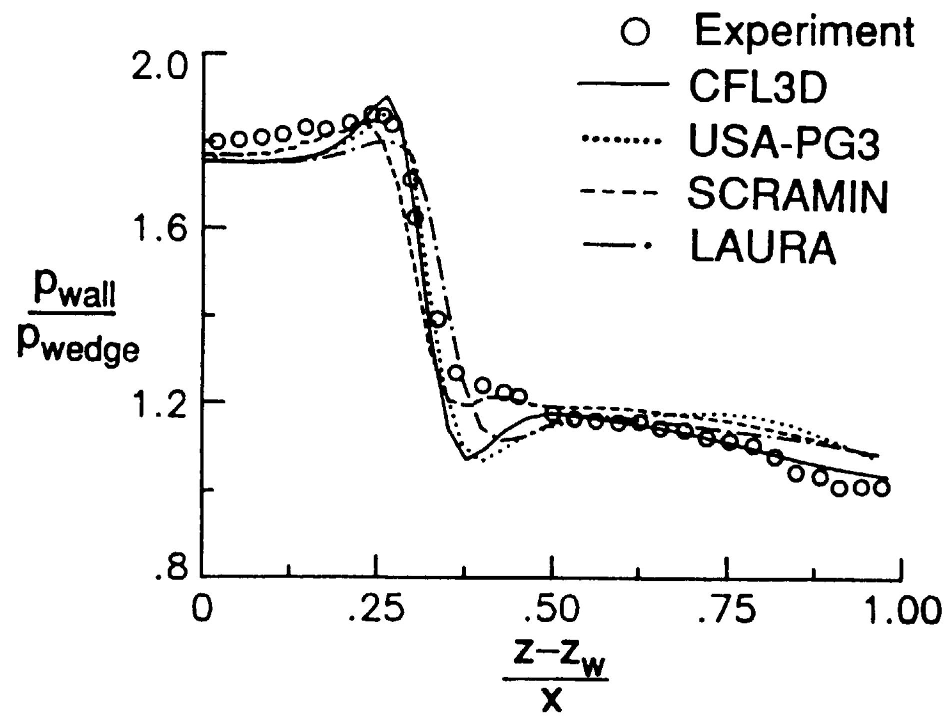


LAMINAR CORNER FLOW

x = 0.0733 m.



Density contours
USA-PG3



Sidewall pressure

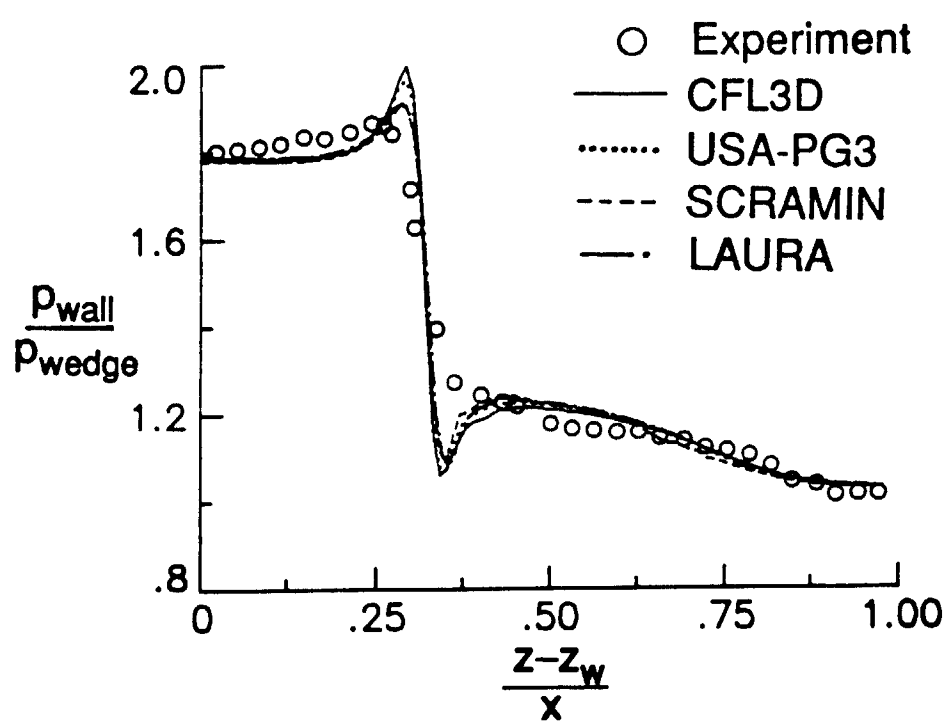
LAMINAR CORNER FLOW

Sidewall pressure

x = 0.0733 m.

Conical flow

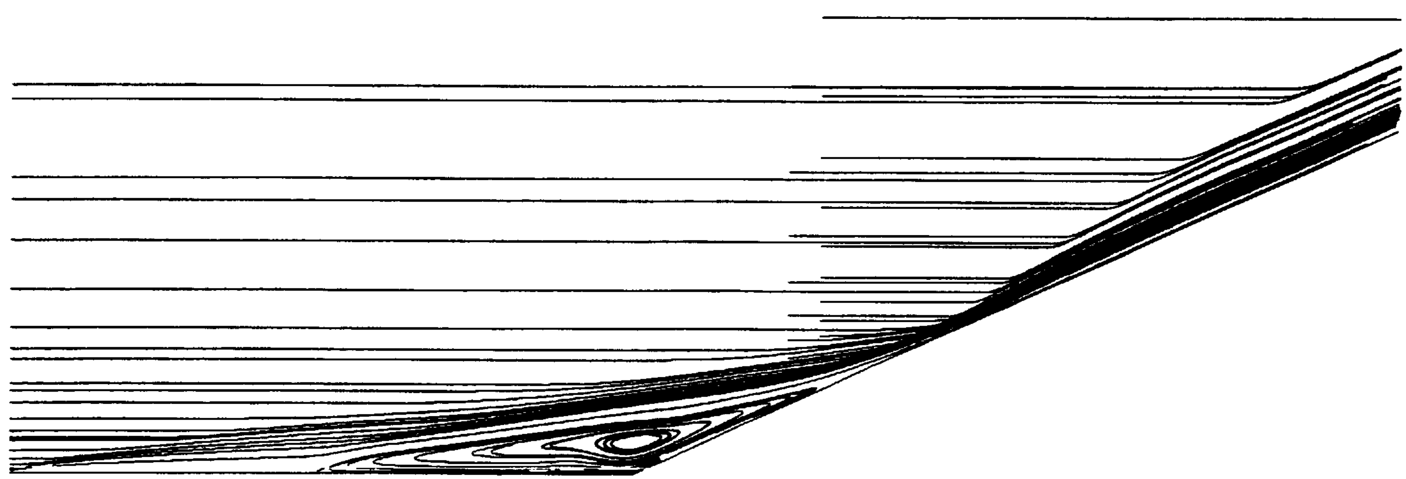
121 x 121 grid



HYPERSONIC COMPRESSION CORNER

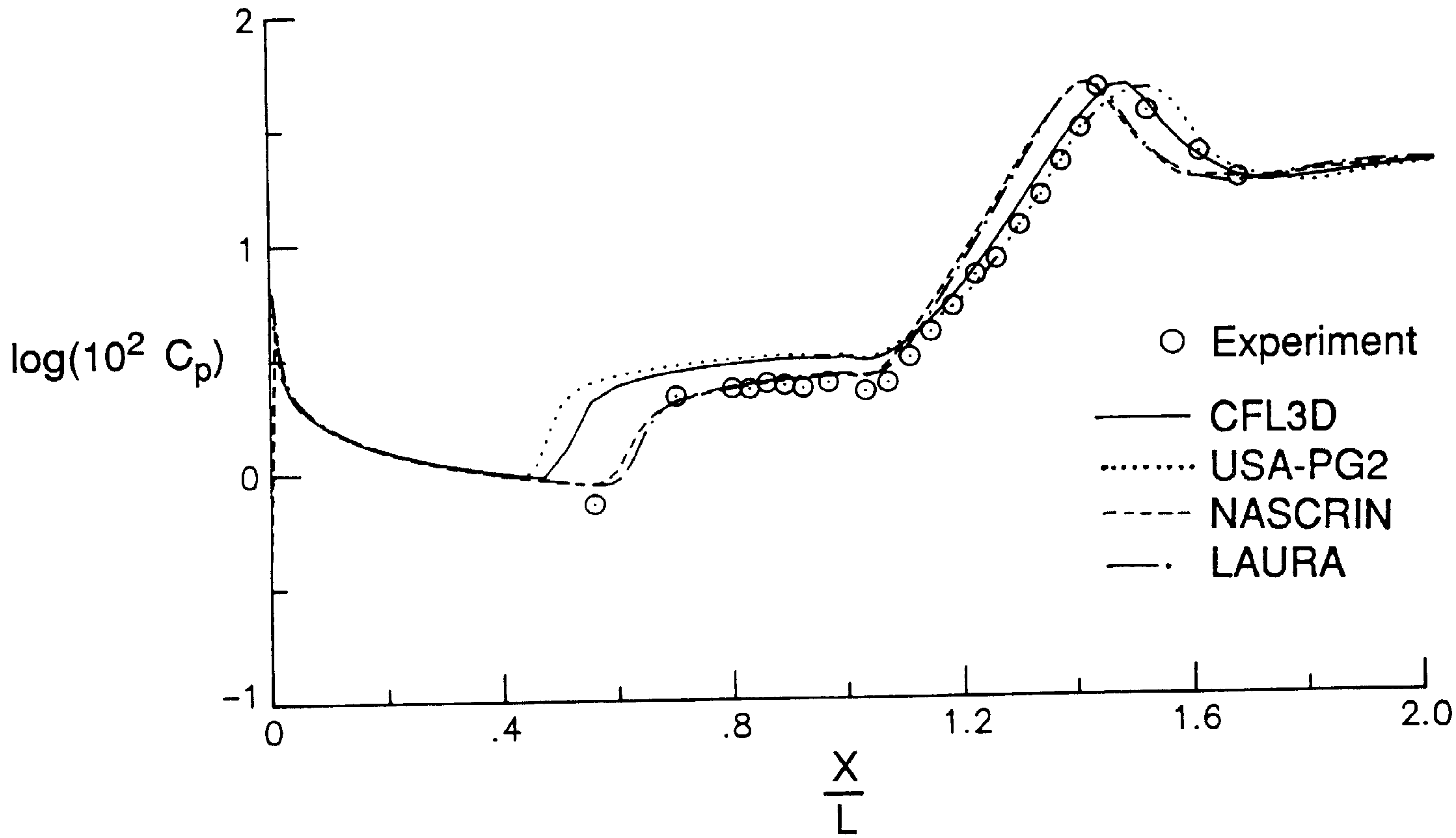
Streamlines
24-degree ramp

USA-PG2



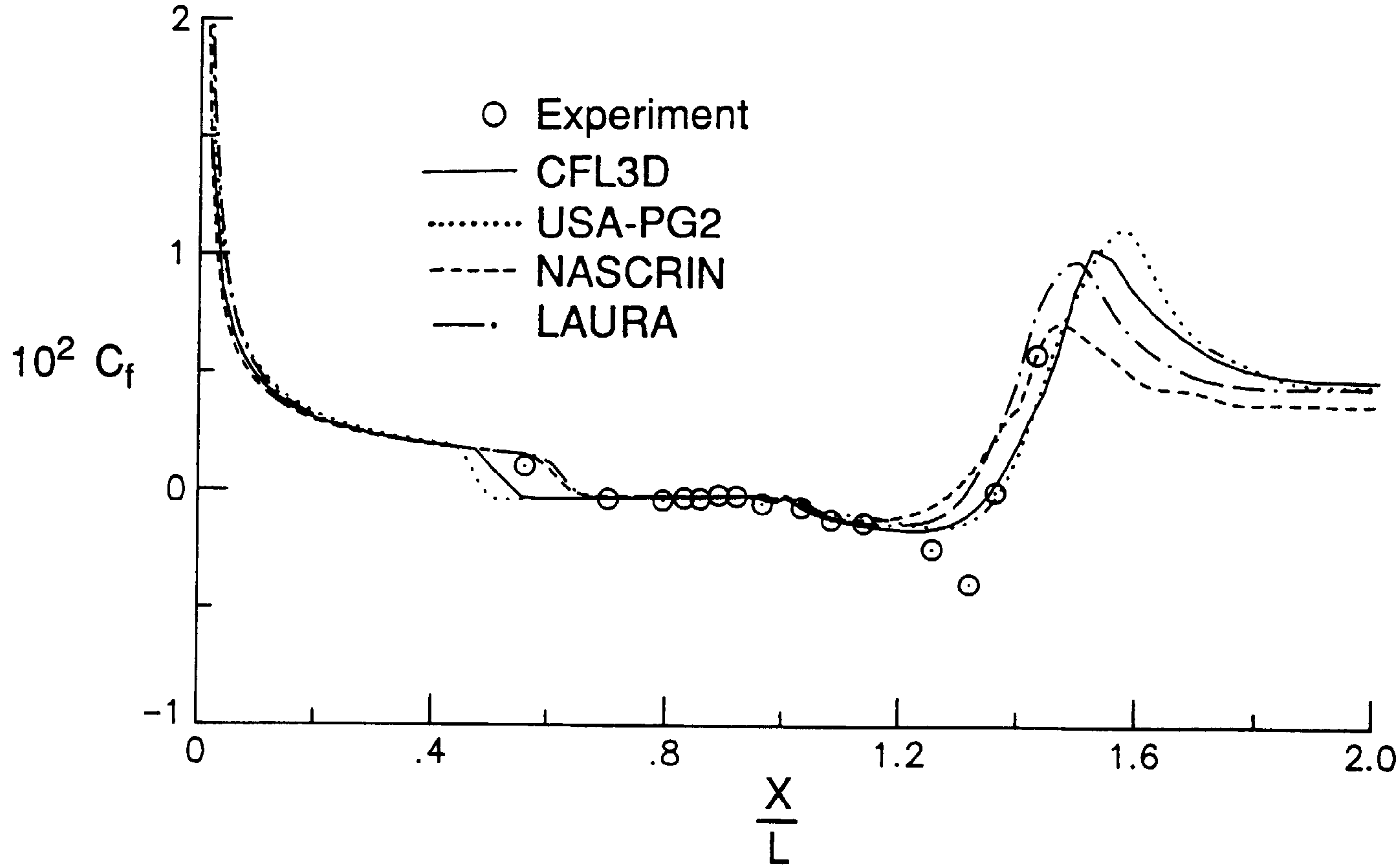
SURFACE PRESSURE

24° ramp
201 x 60 grid



SKIN FRICTION

24° ramp
201 x 60 grid



SUMMARY AND CONCLUSIONS

- A comparative study of four computer codes for the Navier-Stokes equations was performed using three test problems for high-speed flow.

- For the P8 inlet, good agreement was found between the codes. Differences between computation and experiment were possibly due to experimental effects not included.

- Flow structure in 3-D corner was predicted well by all of the codes. Good agreement was found between the solutions for all four codes.

- For the hypersonic compression ramp, the codes predicted the strong interaction structure observed experimentally. A wide variation in the predicted extent of separation was found.